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Overview of fuzzy vehicle routing problems

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Introduction. Various algorithms for solving fuzzy vehicle routing problems are considered. The work objective was to study modern methods for the optimal solution to fuzzy, random and rough vehicle routing problems.

Materials and Methods. The paper reviews fuzzy vehicle routing problems, existing methods and approaches to their solution. The most effective features of some approaches to solving fuzzy vehicle routing problems considering their specificity, are highlighted.

Results. The Fuzzy Vehicle Routing Problem (FVRP) occurs whenever the routing data is vague, unclear, or ambiguous. In many cases, these fuzzy elements can better reflect reality. However, it is very difficult to use Vehicle Routing Problem (VRP) solving algorithms to solve FVRP since several fundamental properties of deterministic problems are no longer fulfilled in FVRP. Therefore, it is required to introduce new models and algorithms of fuzzy programming to solve such problems. Thus, the use of methods of the theory of fuzzy sets will provide successful simulation of the problems containing elements of uncertainty and subjectivity.

Discussion and conclusions. As a result of reviewing various methods and approaches to solving vehicle routing problems, it is concluded that the development and study of new solutions come into sharp focus of researchers nowadays, but the degree of elaboration of various options varies. Methods for the optimal solution of FVRP are limited, in general, to some single fuzzy variable. There is a very limited number of papers that consider a large number of fuzzy variables.

***Keywords**:* fuzzy vehicle routing problem, optimization, fuzzy methods, heuristic algorithms, hybrid algorithms.

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Introduction. The objective of the Vehicle Routing Problem (VRP) is to determine the optimal routes for a vehicle fleet representing an ordered sequence of passing through the loading and unloading points, satisfying some constraints. The restrictions include the demand for goods, the carrying capacity of the vehicle, the maximum time and time windows. Optimality can be assessed in different ways. The most common minimization criteria include total distance, transportation cost, size of the involved vehicle fleet. Since it was first proposed by Dantzig and Ramser in 1959 [1], VRP has attracted widespread attention of experts, academicians and managers in various fields and has

become a subject of study in the field of operations research and optimization of logistics systems. A significant number of successful studies have been conducted.

Initially, most traditional VRP research assumed that all information is deterministic, including customer demand, vehicle fleet characteristics, road conditions, and other data needed to build routes. That is, traditional research has focused on deterministic VRP. However, in a real logistics system, it is difficult to describe VRP information as deterministic due to such factors as weather effects, road conditions, vehicle speed, individual customer needs, as well as the cognitive characteristics of decision makers. Any uncertainty in such problems concentrates on demand, time, etc., and allows them to be classified as nondeterministic VRP. Compared to deterministic, nondeterministic VRPs reflect changes in time and demand, the impact of vehicle routing assignments in real time, which brings them closer to the actual production and logistics processes. The proposed algorithms and conclusions, which are valid for deterministic problems, were usually not applied to nondeterministic ones. Moreover, due to the features described above, the mathematical description of nondeterministic problems is more complicated, and the complexity of finding possible solutions also increases. Therefore, nondeterministic VRPs attract more and more attention and become one of the topical centers of modern VRP research [2].

Definition and classification of nondeterministic vehicle routing problems. Nondeterministic VRP are those in which the planner does not have complete information on the vehicle route until the start of the specified route. That is, some information may be vague, ambiguous, or even unknown. After the initial construction of the vehicle route, the destination of the vehicle route and the task can be changed [3]. Obviously, nondeterministic VRP in this regard is more general than deterministic.

In the related studies, uncertainty includes three main forms: randomness, fuzziness and inaccuracy (roughness) [2]. In some systems, the above uncertainties can coexist. Currently, VRP ambiguity is mainly caused by randomness and fuzziness, and can use fuzzy randomness or random fuzziness to describe the coexistence of randomness and fuzziness in VRP.

With the emergence of numerous generalizations and extensions of VRP, scientists began to consider them under different aspects and classify them according to different standards [4]. Based on the classification of Erbao [5] and the distinguished forms of uncertainty of problems, it is possible to divide nondeterministic VRP into singlet and double ones [6].

Singlet nondeterministic VRP include:

— Stochastic VRP (SVRP) — random vehicle routing problem;

— Fuzzy VRP (FVRP) — fuzzy routing problem;

— Rough VRP — rough vehicle routing problem.

Double nondeterministic VRPs include various pairwise combinations of singlet ones:

— Fuzzyrandom VRP (FRVRP) — fuzzy random vehicle routing problem;

— Randomfuzzy VRP (RFVRP) — random fuzzy vehicle routing problem;

— Fuzzyrough VRP — fuzzy-rough vehicle routing problem;

— Roughfuzzy VRP — rough-fuzzy vehicle routing problem;

— Randomrough VRP — random-rough vehicle routing problem;

— Roughrandom VRP — rough-random vehicle routing problem;

— Dualfuzzy VRP — dual fuzzy vehicle routing problem;

— Dualrandom VRP — double random vehicle routing problem;

— Dualrough VRP — dual rough vehicle routing problem

Random SVRP problems differ from deterministic VRP in that some of the initial data of the problem are not fully defined before the vehicle starts to execute a given route. The planner can derive statistical patterns for this data

based on previous observations or market analysis. That is, some parameters in SVRP are random, mainly such as customer demand, customer service time (time windows), customer distribution, available vehicles, service time, travel time, etc. Gendreau and Laporte [7] provided a good overview of the major variants of SVRP. Currently, research into major SVRP focuses on random demand, random travel time, random customers, and similar problems.

In fuzzy FVRP problems, as in random SVRP problems, there is uncertainty about some of the problem data. However, if randomness presupposes the existence of some well-known statistical regularities that can be used, then fuzziness excludes such regularities. This review is focused specifically on fuzzy vehicle routing problems that are currently of great interest for research.

Research results. Fuzzy vehicle routing problems. The fuzzy vehicle routing problem (FVRP) occurs whenever the routing data is vague, unclear, or ambiguous. For example, when, based on experience, the travel time of a vehicle can be described as “about half an hour”, “between 15 and 20 minutes” and so on. In many cases, such fuzzy elements can better reflect reality. In practice, it can be difficult to obtain accurate values for requests, travel time, number and location of customers, time window boundaries, and other quantities if they obey probabilistic laws. In some new systems, it is also difficult to describe parameters of the problem as random variables due to insufficient data for analyzing the distribution. However, it is very difficult to use deterministic VRP solution algorithms to solve FVRP because several fundamental properties of deterministic problems are no longer fulfilled in FVRP. Therefore, to solve such problems, it is required to introduce new models and algorithms of fuzzy programming. Thus, the use of methods of the theory of fuzzy sets will make it possible to successfully model problems containing elements of uncertainty and subjectivity.

The solution scheme is as follows: first, the information should be made fuzzy, then the idea of fuzzy reasoning to build certain fuzzy criteria and convert the fuzzy variables to their crisp equivalents using defuzzification, is used. Currently, FVRP research is mainly focused on fuzzy demand, fuzzy time windows, fuzzy travel time and fuzzy service time.

VRP with fuzzy demands (VRPFD) is the task of vehicle routing with fuzzy customer demand for goods. VRPFD assumes that the customers who need the service are identified, but their exact demand is uncertain and no statistical rule for their demand can be obtained. There is no doubt that VRPFD is the most investigated area of FVRP. Presumably, the earliest description of VRPFD was proposed by Teodorovich in 1996 [8]. Teodorovich studied VRPFD with one depot, developed fuzzy decision rules based on propensity assessment, proposed the first phase of the solution based on a heuristic sweep algorithm; then, based on the generated solution, he gradually improved it through optimizing routes. Since then, several scientists have used various heuristics to solve YRPFD with some success. Based on fuzzy possibility [3, 9−13], binary approaches [14] and fuzzy confidence [15], they applied an improved heuristic algorithm or a hybrid heuristic algorithm to solve VRPFD. The most widely used algorithm is the modified hybrid genetic algorithm [9–11]. In addition, other algorithms were applied to solve this kind of problems [3, 12–14, 15], such as modified ant colony algorithm, hybrid differential evolutionary algorithm, and improved particle swarm optimization.

VRP with fuzzy time windows (VRPFTW) is a vehicle routing task with fuzzy time windows. VRPFTW is analogous to the |soft-window vehicle routing problem. In it, violation of time windows does not necessarily entail penalties, but there is some uncertainty about long-term consequences for the service quality. For this, either the arrival time or the upper and lower boundaries of time windows is usually considered fuzzy. Wang [16] first applied such a fuzzy theory to the example of a traveling salesman problem — road inspection (Chinese postman) with time windows. Tang and others [17] proposed a VRPFTW mathematical model and a method for its solution in two stages: reduction to traditional VRP with time windows and its solution, and then, solving the problem of improving service based on the

Gomory algorithm and the subgradient optimization method. For a complex VRPFTW with multiple depots and a heterogeneous fleet, a multi-stage heuristic was proposed [18]: customer clustering, routing, vehicle type determination, route planning and improvement using simulated annealing and customer service improvement. Good results were also shown by the particle swarm optimization method [19] and the modified wolf pack algorithm [20].

VRP with fuzzy duetime (VRPFDT) is vehicle routing problem with fuzzy visit time. VRPFDT differs in that time windows are replaced by fuzzy dates. This is due to the fact that time windows in deterministic VRP cannot reflect client preferences in real time. For example, customers may want to receive a service at certain points in time; their satisfaction may be reduced if the service is offered ahead or behind time. Hence, there is fuzzy time to visit. In 1995, Cheng and others [21] first proposed the concept of VRPFDT and built a VRP model under the conditions of single export or single delivery, proposed an improved hybrid genetic algorithm for solving such a VRP model using push-bump-throw procedures. Thereafter, Teodorovich [22] investigated a fuzzy dynamic problem of constructing routes between the corresponding points of export and delivery (Dial-A-RideProblem) and additionally analyzed VRP with fuzzy visit time and fuzzy travel time. Besides, other methods, such as heuristic insertion algorithm, modified ant colony algorithm, genetic algorithm, etc., play an important role in solving VRPFDT [23, 24].

VRP withfuzzytraveltime (VRPFT) is a vehicle routing problem with fuzzy travel time. In VRPFT, the travel time of a vehicle when it is assigned a route is fuzzy, while other parameters are specified and deterministic. Research on VRPFT is currently scarce and includes only a few publications. Teodorovic first introduced fuzzy theory in VRPFT in 1991 [25] suggesting that travel times between locations are fuzzy variables. He built a VRPFT model and proposed Clarke-Wright algorithm to solve it. Based on fuzzy possibility and reliability, Chen [26] and Zheng [27] studied VRPFT with time windows and proposed an imperialist competitive algorithm and a hybrid genetic algorithm. Jia [28] used a genetic algorithm to solve VRPFT based on the I_L. measurement method. Brito [29] and Zhang [30] developed a hybrid genetic algorithm for solving VRPFT based on fuzzy logic.

VRP withfuzzyservicetime (VRPFST) is a vehicle routing problem with fuzzy service time. VRPFST occurs in companies that do not have accurate information on the service time required for each incoming order. However, decisions made should take into account the estimated service time and available resources, including working hours and the number of vehicles available. For a dynamic version of this problem, Kuo and others [31] applied successfully a fuzzy ant colony algorithm with a built-in cluster insert procedure.

In addition, some literature sources investigated VRP with fuzzy cost coefficients [32], VRP with fuzzy time windows [33], VRP with simultaneously fuzzy travel time and visit time [22, 34], and VRP with fuzzy travel time and visit time [35], etc.

In recent years, due to the concern of the world community with environmental problems, the direction of green transportation logistics is gaining popularity [36], within which a green vehicle routing problem – G-VRP [37] arose. It is aimed at finding a balance between economic benefits and environmental impact. For a fuzzy version of this problem, a hybrid genetic algorithm combined with fuzzy modeling was recently proposed [38].

Discussion and Conclusions. Based on the material presented in the review, it can be concluded that the study of fuzzy vehicle routing problems is attracting more and more attention, but the degree of development of its individual options varies. It should be noted that to date, FVRP research is mostly limited to one fuzzy variable, such as fuzzy demand or fuzzy customer visit times. There are comparatively few studies that comprehensively consider a larger number of fuzzy variables [22, 34, 35]. Another problem is that the role of the distributor experience in FVRP is rarely considered, which makes practical applicability negligible. To bridge the gap between theoretical research and practical application, it is required to enhance integrated research. It also leaves open issues on combining these studies with

some new technologies such as e-commerce, the Internet of Things and big data. In addition, a system for evaluating the algorithms for solving FVRP has not yet been developed.

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Yu. O. Chernyshev: academic advising; formulation of the basic research concept and the structure of the paper. V. N. Kubil: collection and analysis of literature data; critical analysis. A. V. Trebukhin: literature analysis; participation in research; editing the text of the paper.

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